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Abstract: Wild beluga whistle source levels (SLs) are estimated from 52 three-dimensional (3D) localized calls using a 4-hydrophone array. The probability distribution functions of the root-mean-square (rms) SL in the time domain, and the peak, the strongest 3-dB, and 10-dB SLs from the spectrogram, were non-Gaussian. The average rms SL was 143.8 ± 6.7 dB re 1 μPa at 1 m. SL spectral metrics were, respectively, 145.8 ± 8 dB, 143.2 ± 7.1 dB, and 138.5 ± 6.9 dB re 1 $\mu\text{Pa}^2\cdot\text{Hz}^{-1}$ at 1 m.

[CFM]
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1. Introduction

Beluga whales (*Delphinapterus leucas*) have a circumpolar distribution in arctic and sub-arctic waters that ranges from 47°N to 80°N latitude, along the coasts of Alaska, Canada, Greenland, and Russia. Some beluga whale sub-populations, such as those from Eastern Hudson Bay, Ungava Bay, and St. Lawrence Estuary, are on the list of endangered species of the Committee on the Status of Endangered Wildlife in Canada.[1] Therefore, these populations benefit from recovery programs that include scientific studies to determine the causes of their decline and fill knowledge gaps on their ecology.

Passive Acoustic Monitoring (PAM) is nowadays a well-established method to study cetaceans through the sounds they produce.[2] PAM has been extensively used to study free-ranging beluga whales at various locations. Especially, PAM has been successfully applied to study the properties of beluga echolocation clicks[3] and click-trains,[4] to describe their call repertoire and characterize their properties (frequency content, inflexion points, duration).[5–7] It has also been used to determine their space-time distribution[8–10] and to estimate the masking effects of their sounds by anthropogenic noises.[11,12]

One of the basic parameters involved in PAM applications is the energy level of the emitting source. This determines, among others, the communication space of the animals, the signal-to-noise ratio (SNR) and masking, as well as the PAM detection range and probability function for density estimation. To our knowledge, the source level (SL) of wild beluga whistles has not been documented so far. In this letter, we contribute to fill this knowledge gap by estimating the SL of whistles produced by free-ranging beluga whales from the Saguenay-St. Lawrence marine park (Canada).

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Section 2 presents the recording setup and methods used for localizing the whistles and for estimating their SLs. Results are then presented and discussed in Sec. 3.

2. Materials and methods

2.1 Data acquisition

The data were recorded in May 2009 at the Saguenay fjord mouth, in the St. Lawrence estuary [Fig. 1(a)]. They were acquired by a cabled coastal array connected to a data acquisition board (IOTech DaqBoard 3000/USB, Cleveland, Ohio) that simultaneously recorded the signals coming from four hydrophones (HTI 96 MIN, High Tech Inc., Gulfport, MS). The signals were digitized with 16 bit and a sampling frequency of 48 kHz, and saved as WAV files on a PC. The array was tilted according to the natural slope of the fjord and had an aperture of about 200 m. The four hydrophones were at 28, 69, 134, and 141 m depths, and were kept about 4 m above the seafloor. This setup allows the absolute localization of belugas that are close to the array. Precise hydrophone positions were calculated from acoustic localization using known sources emitted at eight different positions around the array. A more detailed description of this setup and of the calibration procedure can be found in Roy *et al.* [3]

2.2 Pre-processing

We manually annotated 52 beluga whale whistles by visually scanning the spectrogram of the recorded data. These whistles were chosen because they were not mixed with other sounds, they had good SNRs, and they were recorded on all four hydrophones. Whistles were then bandpass filtered between 1.5 and 5 kHz, the frequency band where they were concentrated.

2.3 Source position estimation

The three-dimensional (3D) location of the belugas was performed by computing the time-difference-of-arrivals (TDOAs) of the whistles on the four hydrophones. The TDOAs were estimated from a modified cross-correlation function known as cross-recurrence plot analysis (CRPA) between pairs of hydrophones.[13] This CRPA method performs a similarity analysis between the waveform received by each hydrophone, and detects a series of samples that are similar on each pair of hydrophones. The TDOA is then estimated from this detected series. Such an approach appears to be more robust than the classical autocorrelation when signals have high amplitude modulations[13] as it is the case with cetacean whistles. The six TDOAs obtained for each whistle were then validated and misestimated TDOAs were discarded.

For the localization we proceeded as in Roy *et al.*[3] The space around the array was discretized according to a 3D grid with a mesh size of 10 m horizontally and 5 m vertically. Then, we calculated the theoretical TDOAs by propagating sources at the nodes of the grid to the location of the hydrophones. A sound speed of 1444 m s^{-1} based on measured sound speed profile was used [Fig. 1(b)] and direct straight trajectories were assumed. These were reasonable assumptions because the belugas were close to the array [Fig. 1(c)]. Finally, the source location was determined by minimizing the

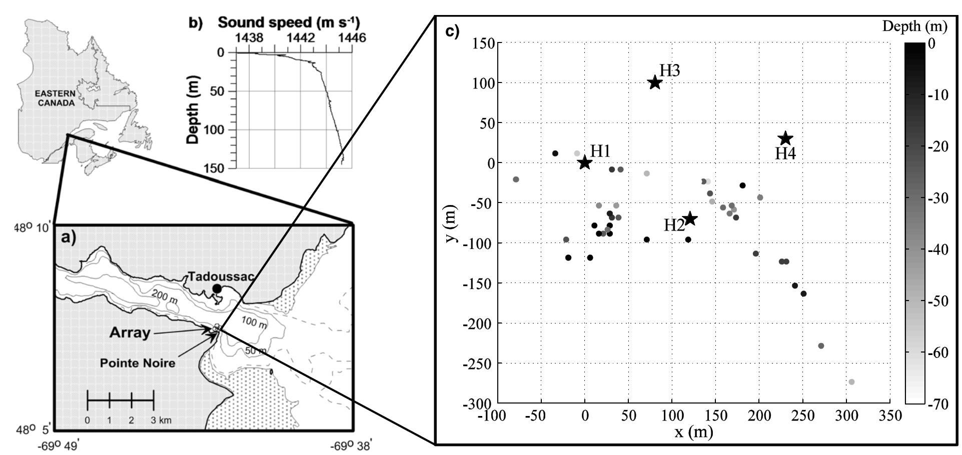

Fig. 1. (Color online) (a) Position of the array at the Saguenay fjord mouth in the St. Lawrence estuary; (b) sound speed profile measured during the deployment of the array; (c) location of the 52 annotated beluga whistles and of the 4 hydrophones.

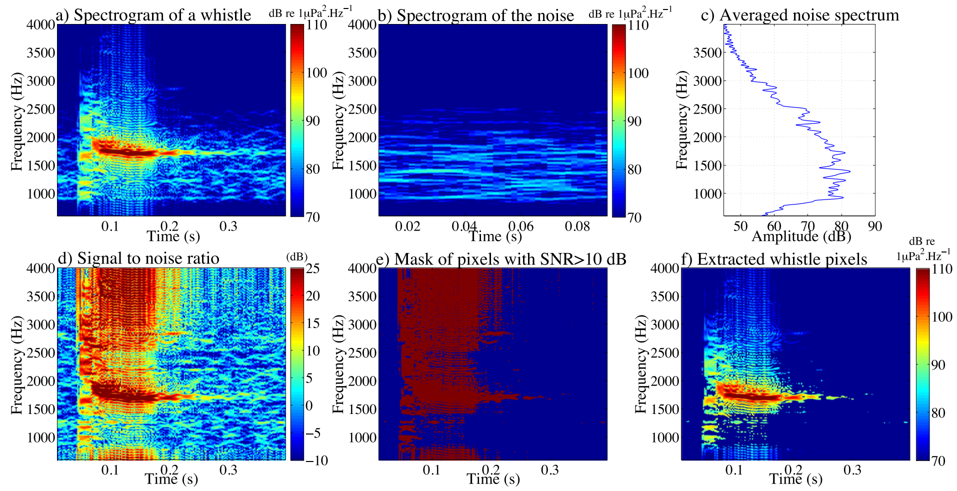

Fig. 2. (Color online) Steps followed to extract from the spectrogram all the pixels associated to a beluga whale whistle and having a SNR > 10 dB.

Euclidean distance between the measured TDOAs and the set of precalculated TDOAs.

2.4 SL estimation

As PAM users are usually interested in knowing the maximum detection range of PAM systems and the active communication space of cetaceans, we focused on the four following SL metrics: root-mean-square (rms) SL, spectral peak, strongest 3-dB, and 10-dB SLs. The SLs were calculated for each hydrophone as follows: $\mathrm{SL} = \mathrm{RL} + 20\log_{10}(r)$, with RL the corresponding received level and r the range between the sound source and each hydrophone. Transmission loss was assumed to be spherical spreading. We did not compensate for the absorption in the water and fading due to multipath propagation.

The rms SL was computed in a window that makes up 80% of the total cumulative energy of the signal.[14] However, one has to be aware that this metric can sometimes be biased, as it is very dependent of the length of the averaging window that is used and of the criteria chosen to determine this latter.[14]

The three other SL metrics were measured on the spectrogram, whose settings included a 1024 points running window, a 90% overlap, and 16 384 zero-padded fast Fourier transform [Fig. 2(a)]. Only the pixels of the spectrogram associated to the whistles and having a SNR > 10 dB were considered for the SL estimation. To identify these particular pixels, we first calculated the spectrogram of the noise with the same parameters as above, in a 0.1 s window following each whistle [Fig. 2(b)]. The mean level of this noise spectrogram was then computed in each frequency band to estimate the average noise level by frequency band [Fig. 2(c)]. We then subtracted this average noise level from the initial spectrogram [Fig. 2(a)] to get the SNR of each time-frequency bin of the spectrogram [Fig. 2(d)]. This SNR spectrogram was thresholded to retain pixels with a SNR > 10 dB, forming the mask of the whistle [Fig. 2(e), red]. Finally, we applied the mask on the initial spectrogram of the whistle [Fig. 2(a)] to extract the pixels of the spectrogram associated to the whistles and having a SNR > 10 dB [Fig. 2(f)].

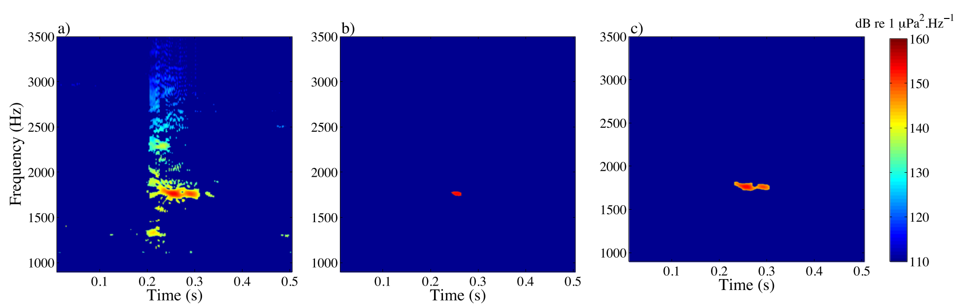

Fig. 3. (Color online) Example of thresholded spectrogram (a) with the strongest 3-dB SLs (b) and 10-dB SLs (c).

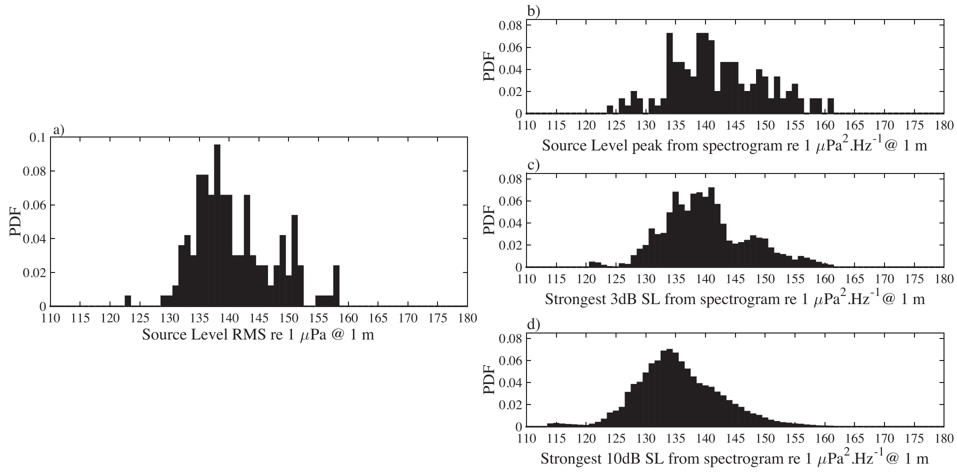

Fig. 4. Distribution of the estimated SLs on the four hydrophones: (a) rms SLs; (b) spectral peak SL; (c) strongest 3-dB SLs; (d) strongest 10-dB SLs.

The spectral peak SL estimation follows the one proposed by Rossong and Terhune,[15] First, we measured the peak SL on the loudest of the four hydrophones and at the frequency of the highest amplitude in the whistle. The peak SL was then measured at this frequency for the other three hydrophones.

The strongest 3- and 10-dB SLs from the thresholded spectrogram were extracted independently for each hydrophone. These are not classical SL metrics but we believe they are of interest because spectrogram segmentation methods are often used to detect whistling activities by PAM and these SLs provide information on the level of the useful pixels for the detection. We first measured the peak SL on the thresholded spectrogram of each hydrophone and then extracted all the pixels that were within the range [$SL_{peak}-3$ dB; SL_{peak}] and [$SL_{peak}-10$ dB; SL_{peak}] (Fig. 3).

3. Results and discussion

For each of the 52 annotated whistles, the 4 SL metrics were estimated for each hydrophone and their probability density functions (PDFs) were computed (Fig. 4, Table 1). The mean whistle rms SL is 143.8 ($\pm$6.7) dB re 1 μPa_{rms} at 1 m, the mean spectral peak SL is 145.8 ($\pm$8) dB re 1 μPa^2 Hz^{-1} at 1 m, and the strongest 3- and 10-dB SLs have an average of 143.2 ($\pm$7.1) dB re 1 μPa^2 Hz^{-1} at 1 m and 138.5 ($\pm$6.9) dB re 1 μPa^2 Hz^{-1} at 1 m, respectively.

SL metric PDFs are non-Gaussian and have a first mode at lower SLs followed by a secondary mode or a plateau at higher SLs [Figs. 4(a)–4(d)]. These particular PDFs might result from propagation effects that modulate the whistle amplitude. For instance, the average shift between the peak-to-peak SL PDF (not shown here) and the rms SL PDF [Fig. 4(a)] was found to be of 20.6 dB, whereas, without modulation, a pure cosine signal would have produced a shift of 9 dB. Another hypothesis to explain the SL PDFs is that the SL depends on whistle type and of variations in the emission levels as for killer whales.[16] Further analysis with much more whistles would be needed to confirm these hypotheses. At last, the directivity of the beluga whistles might also be involved in the dispersion of these PDFs. Such a directivity has already been observed for other species.[17,18] With directional sources, off beam axis receiving angles and corresponding lower SLs are more probable than on-axis ones. This could produce the observed SL PDFs.

Table 1. Percentiles of the rms SLs (dB re 1 μPa at 1 m), and spectral peak SLs, strongest 3-dB and 10-dB SLs (dB re 1 μPa^2 Hz^{-1} at 1 m).

Percentiles	Min	10th	20th	30th	40th	50th	60th	70th	80th	90th	100th
SL_{rms}	123.5	133.3	135.4	136.6	137.9	139.3	140.8	143.2	147.5	151.0	158.2
$SL_{spectral\ peak}$	123.7	133.3	135.1	137.6	139.4	141.1	143.5	145.9	149.1	153.3	161.4
$SL_{strongest\ 3\ dB}$	120.7	131.6	134.4	135.9	137.7	139.2	140.8	142.4	146.2	150.1	161.5
$SL_{strongest\ 10\ dB}$	113.7	127.5	129.9	131.7	133.3	134.7	136.4	138.5	141.2	144.8	161.5

Overall, the observed whistle SLs fall within the range of previous estimates for other species. Minimum, maximum, median, and mean whistle SLs are similar to those of white beaked dolphins,[18] killer whales,[16] bottlenose, and spotted dolphins.[19]

Acknowledgments

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